Towards determining the parameters of layer with scattering irregularities that cause coherent echo, based on the Irkutsk Incoherent Scatter radar data.

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Abstract

In the paper we have presented a technique of determining the scattering irregularities (that cause coherent echo) layer parameters using the Irkutsk IS radar data. It is shown that our technique has necessary accuracy (for height and thickness - about 2.5 km, for aspect sensitivity - 5dB/degree). Processing of the experiments 25-26.12.1998 and 15-16.07.2000 has shown a good agreement of data calculated with the data obtained by other investigators: an average layer height is 110-120km, average layer thickness 5km, average aspect sensitivity - 15dB/degree. The investigation of the experiments with high temporal resolution allowed us to observe temporal variations of the irregularities layer parameters. The average thickness and height of the layer does not contradict the data obtained by other investigators. The investigation of the experiments with high temporal resolution allowed to detect time variations of the layer parameters. The temporal variations of the aspect sensitivity are observed by us for the first time and requires additional investigations.

1 Introduction.

One of the most important effects that affects to the ionospheric and transionospheric radiowave propagation is a scattering on the inhomogeneities of different scales. That is why, when studying the ionosphere they pay valuable attention to the diagnostics of the ionospheric inhomogeneities. At middle latitudes, the least observed but the most affecting to the radiosignals propagation are the irregularities elongated with the Earth magnetic field. Scattering by these irregularities has high aspect sensitivity, that causes a strong dependence of scattered signal amplitude on transmitted and received waves orientation. One of the physical mechanisms of creation of such inhomogeneities, elongated with the Earth magnetic field, in the ionospheric E-layer is the growth of two-stream and gradient-drift irregularities. The necessary conditions for the growth of these irregularities are powerful electric field, high electron-to-ion velocity and high electron density gradients existence [Farley, 1963, Buneman, 1963]. Such inhomogeneities are observed at high and equatorial latitudes and could affect to the received signal from 8MHz to 1GHz [Haldoupis, 1989]. The conditions for arising these inhomogeneities at mid-latitudes most frequently are satisfied during strong geomagnetic disturbances. At polar and equatorial latitudes these requirements are satisfied in less disturbed conditions [Haldoupis, 1989, St.-Maurice et al., 1989]. Radiosignals scattered at these inhomogeneities are known as radioaurora, or coherent echo (CE).The CE signals have been observed at the Irkutsk IS radar since 1998. During the last time at the Irkutsk IS radar a number of strong geomagnetic disturbances accompanied with CE observations have been observed [Zolotukhina et al.,2007].

The experiment geometry is shown at fig.1. Irkutsk IS radar is a monostatic tool and transmits a periodical sequence of radiopulses. It receives scattered signal after each transmitted pulse and averages scattered power from pulse to pulse. Wide antenna patter allows us to analyze the signal scattered from a big range of radar ranges almost at the same time with a good time and spatial resolution (1-2 minutes and 15 km. correspondingly). More detailed the experiment geometry and the radar characteristics was described at [Potekhin et al., 1999].

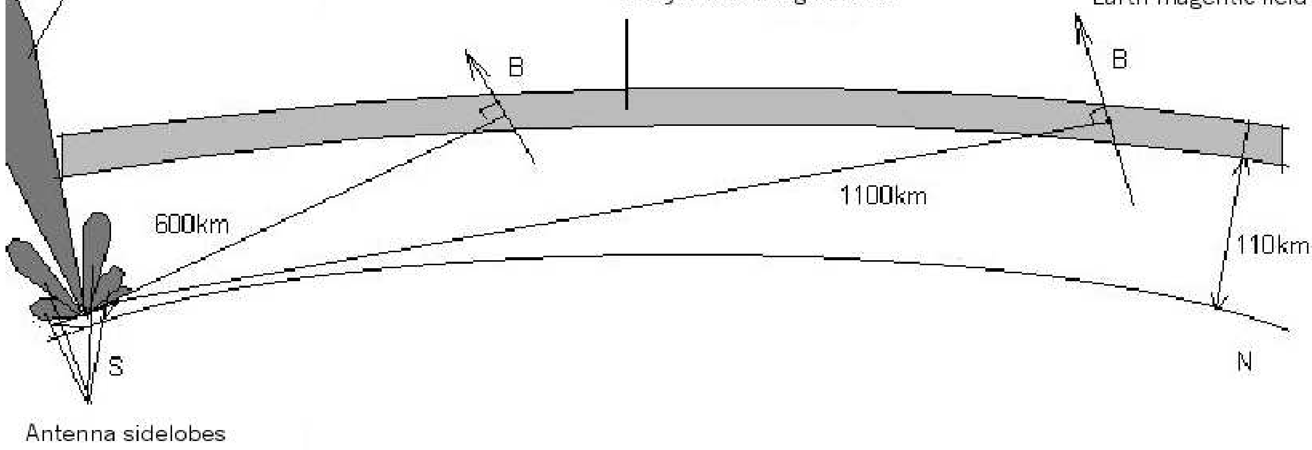

Fig 1. The geometry of the experiment

Due to the Irkutsk IS radar location and construction peculiarities [Zherbtsov et al., 2002] the scattered CE signal usually has two peaks in the power profile - at ranges 550 and 1100 km correspondingly, at these ranges the line-of-sight is most close to the perpendicular to the magnetic field. As preliminary analysis has shown the peaks shape and location depend on the characteristics of scattering irregularities. The aim of this paper is to determine scattering irregularities characteristics within the therm of a standard model. The task is not a new one. Such experiments have been made at some radars with narrow (or steerable) antenna pattern [St.-Maurice et al., 1989, Foster et al., 1992]. This allow to determine characteristics of scattering irregularities in terms of layer of irregularities - height of the layer is approximately 110km, layer thickness is about 10km, sometimes a number of thin layers has been observed at the same time [St.-Maurice et al., 1989]. The aspect sensitivity has been investigated at these frequencies by other investigators and gives average estimates of about 15 dB/degree [Foster et al., 1992]. Due to the Irkutsk IS radar antenna pattern peculiarities the techniques used at other radars do not work - antenna pattern at lower side lobes (used to receive CE signals) is close to an isotropic one. That is why the aim of the paper is to obtain a stable algorithm for determining the characteristics of the layer with irregularities - the height, the thickness and the aspect sensitivity of irregularities from the power profile dependence on range.

2 The model of the scattered signal.

For solving the declared aim the numerical modelling has been made to obtain a dependence of CE power profile on radar range and scattering layer characteristics. The observed power profile is produced by scattering on irregularities generated during strong geomagnetic disturbances in ionospheric E-layer and elongated with the Earth magnetic field.

The model (1) used to describe average power of the scattered signal on radar range (power profile $P(R)$) includes aspect sensitivity of scattered signal in exponential form [Foster et al., 1992] (with accuracy of an arbitrary multiplier):

$$P(R) = f(E)\int |u(2\frac{R-r}{c})|^2 |g(\frac{\vec{r}}{r})|^2 exp(-\frac{(h-h_0)^2}{(\triangle h)^2}) exp(-(\frac{arccos(\frac{\vec{r}\vec{B}}{rB})}{\triangle\varphi})^2)\frac{d\vec{r}}{r^2} \quad (1)$$

$f(E)$- dependence on the electric field;
$u(2\frac{R-r}{c})$-sounding signal pulse shape;
$g(\frac{\vec{r}}{r})$-antenna pattern;
h- height at the scattering point;
h_0- layer height, $\triangle h$-layer thickness, $\triangle\varphi$- aspect sensitivity;
$\vec{B}$- vector of magnetic field;
$\vec{r}$- vector from the observation point to the scattering point.

The calculation has been made is based on the international reference model for magnetic field (IGRF) and the Irkutsk IS radar antenna pattern model (currently used by us) $g(\frac{\vec{r}}{r})$. As a model of scattering irregularities a Gaussian layer with irregularities has been chosen, characterized by its height h_0 and thickness $\triangle h$. Spectral density of the irregularities, which defines the aspect sensitivity of the scattered signal power from the magnetic field was chosen in exponential form. This dependence is defined by the aspect sensitivity $\triangle\varphi$ and by the angle between line-of-sight and magnetic field $\vec{B}$. The electric field E effects in the scattered power is included as some multiplier $f(E)$. The shape of the transmitted pulse $u(t)$ was also taken into consideration. The coordinate center $\vec{r} = 0$ corresponds to the antenna center.

At fig.1 power profiles, which were obtained by the described model for different parameters $h_0, \triangle h, \triangle\varphi$, are shown. The red-color line corresponds to the average parameters of irregularities. From this figure one can see that profiles for the different parameters can change drastically.

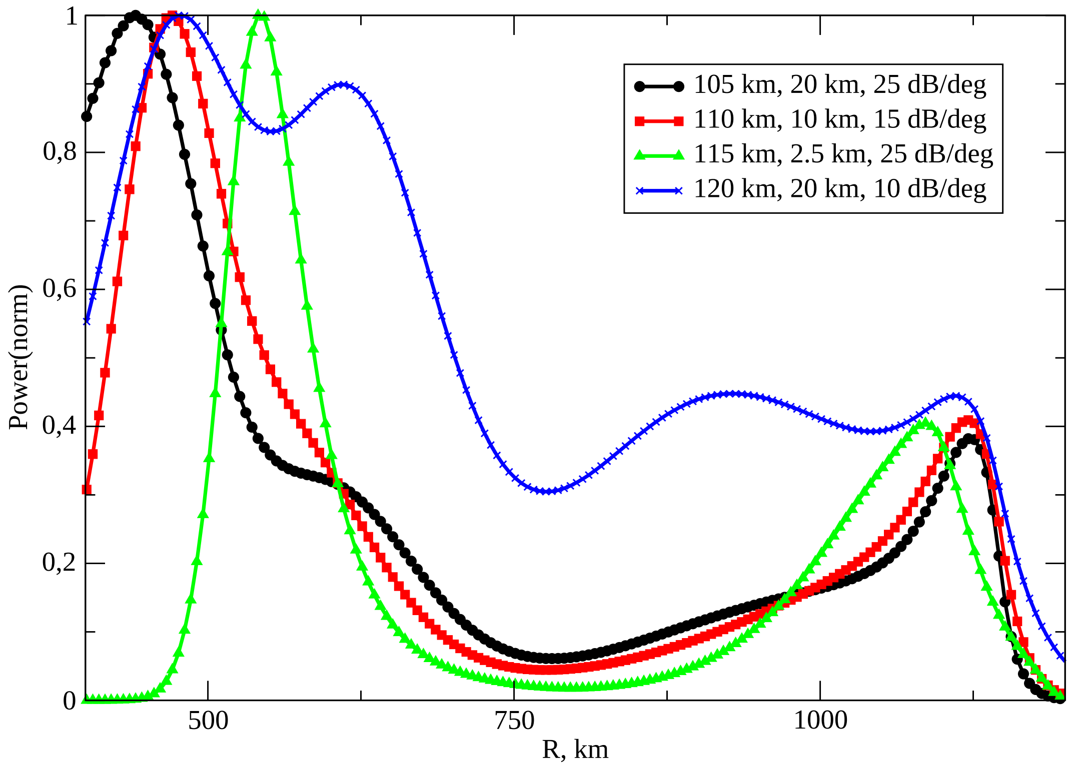

Fig.2 Model power profiles for the different model values

The search of unknown parameters $h_0, \triangle h, \triangle\varphi$ over the experimentally measured power profiles was made by the search of the correlation coefficient over the number of preliminary calculated model profiles (2). The indexes *mod* and *exp* for power profiles corresponds to the power profiles calculated from the model and for experimental power profiles correspondingly. The accumulation $\sum\limits_i$ should be made over the radar range discreets $P_i = P(R_i, h_0, \triangle h, \triangle\varphi)$.

$$K(h_0, \triangle h, \triangle\varphi) = \frac{\sum\limits_i (P_i^{exp} * (P_i^{mod} + C))}{\sqrt{\sum\limits_i (P_i^{exp}) * \sum\limits_i (P_i^{mod} + C)^2}} \tag{2}$$

The search of the constant C which defines the noise level (ionospheric and electronical noise) was made according to the functional (2) maximum condition in form (3). It could be rewritten in form of the linear equation for C (4):

$$\frac{dK}{dC} = 0 \tag{3}$$

$$C = \frac{\sum\limits_i P_i^{exp} * \sum\limits_i (P_i^{mod})^2 - \sum\limits_i (P_i^{exp} * P_i^{mod}) * \sum\limits_i P_i^{mod}}{n * \sum\limits_i (P_i^{exp} * P_i^{mod}) - \sum\limits_i P_i^{mod} * \sum\limits_i P_i^{exp}} \tag{4}$$

The range of layer height values was chosen from 100 to 125 km, layer thickness - from 2.5 to 20 km, aspect sensitivity - from10 t0 25dB/grad. With the step of 2.5 km for height and thickness, and 2.5dB/grad for aspect sensitivity the model power profiles have been calculated and summarized as a matrix. To check the stability of the solution, including the presence of the noise, a number of tests has been made to test its stability at all model parameters combinations. The testing has been made by adding noises which correspond both to the ionospheric noise and statistical noise which arise due to limited number of samples used for averaging. During the testing 3 variants of the noise have been used. Averaging has been made over 500 single soundings:

1. The noise with constant average amplitude that corresponds to the ionospheric noise. In this case the noise amplitude was 2% from the power profile maximum.

2. The noise with amplitude that is proportional to the power signal at given radar range, it corresponds to the statical noises. The amplitude of the noise was 4% from the current power profile value (at given height).

maximum, frequency was within actual filters bandwidth used for experiments.

The error distributions for testing results are shown at fig.3. Green color corresponds to the low-frequency noise, blue color corresponds to the ionospheric-like noise, magenta color corresponds to the statistical noise. At the left top of the figure - the results for the layer height, at the right top - for the layer thickness, at the bottom - for the aspect sensitivity. From this figure it is clear that aspect sensitivity is less stable parameter to calculate, the most stable parameters are layer height and thickness. When calculating aspect sensitivity, the algorithm provides less stable results, but inspite of this it gives a good precision, and errors with amplitudes more than model discreet 2.5dB/degree do not exceed 2% of all the tested samples. The algorithm provides less stability for low-frequency noises.

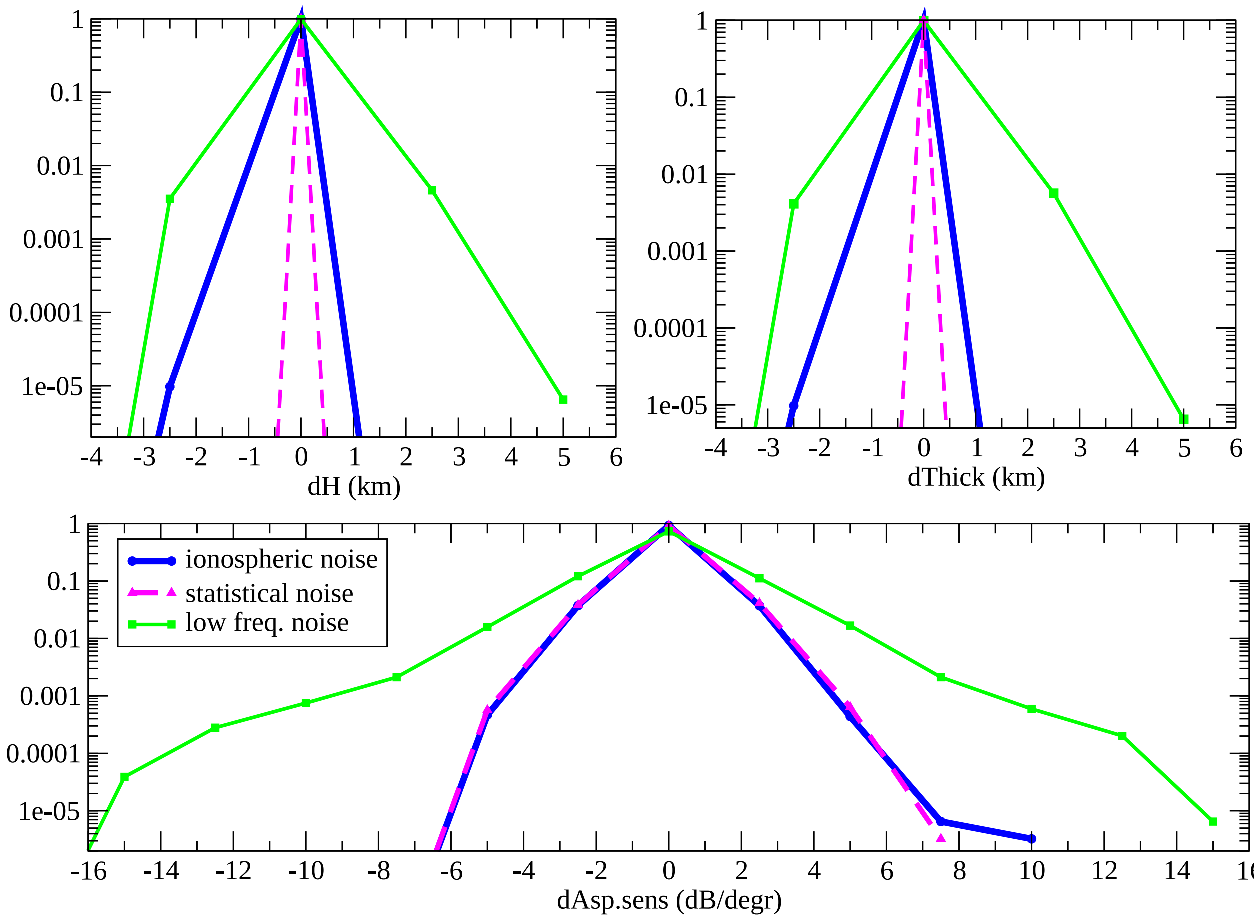

Fig.3 Errors distribution of inverting of noised model data.

In addition to testing the model inversion accuracy in presence of the noise, a testing of the experimental data was made in presence of the same noises. The obtained results differ from the results obtained when inverting the model profiles in presence of the noise. The most stable parameters are still layer height and thickness. The less stable is aspect sensitivity, that was calculated with unsuccessful accuracy. As opposed to the testing of the model data, the testing of the experimental data provides non-symmetrical error distributions, and in number of cases does not provide the necessary accuracy. This effect could be explained by the fact that a number of cases we could not define as 'coherent echo'. Inspite of this the number of parameters erroneously defined (that are out of model accuracy) is pretty small, and this allows us to suggest the model as adequate to the experiment data.

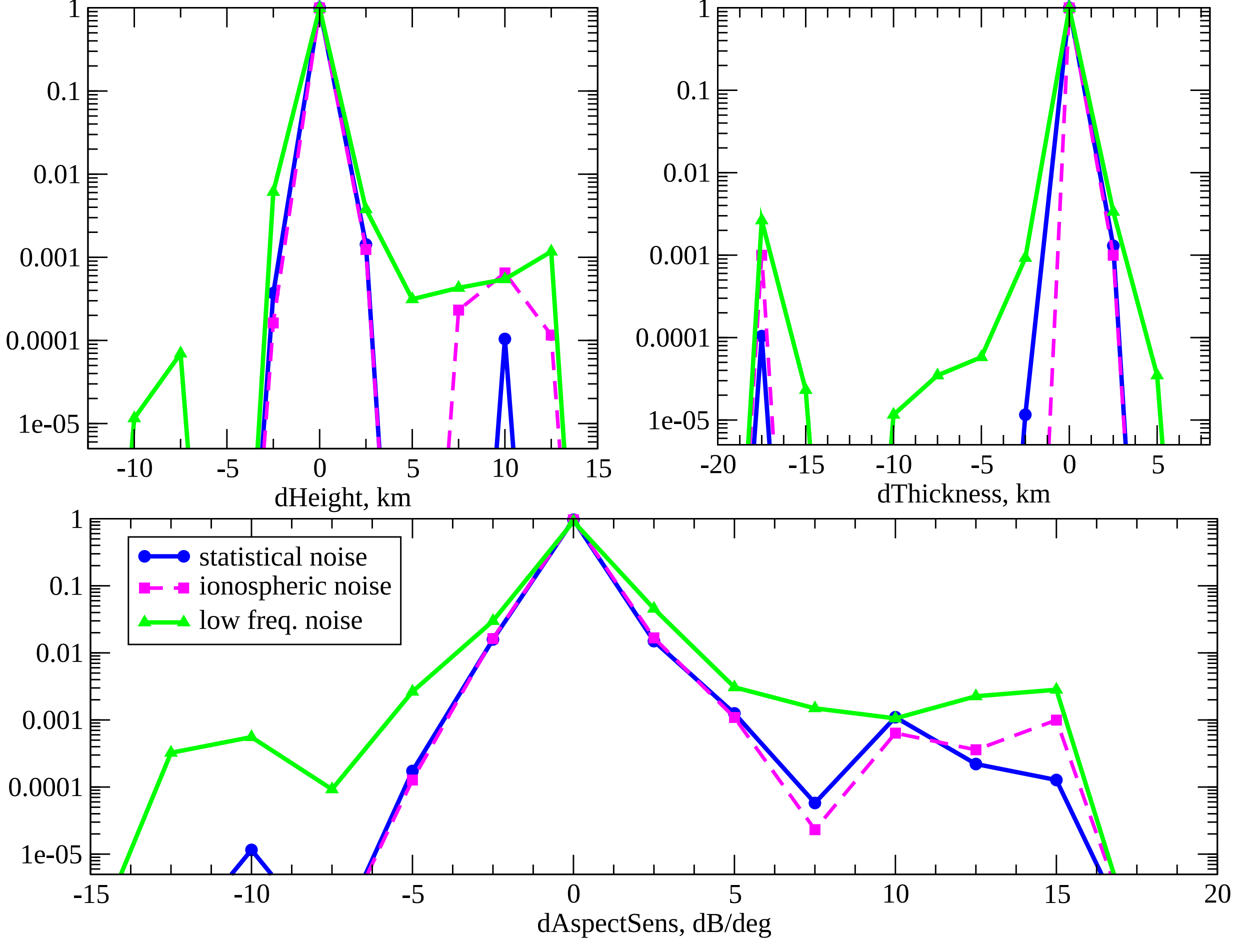

Fig.4a Errors distribution of inverting noised experimental data (25-26.09.1998 experiment)

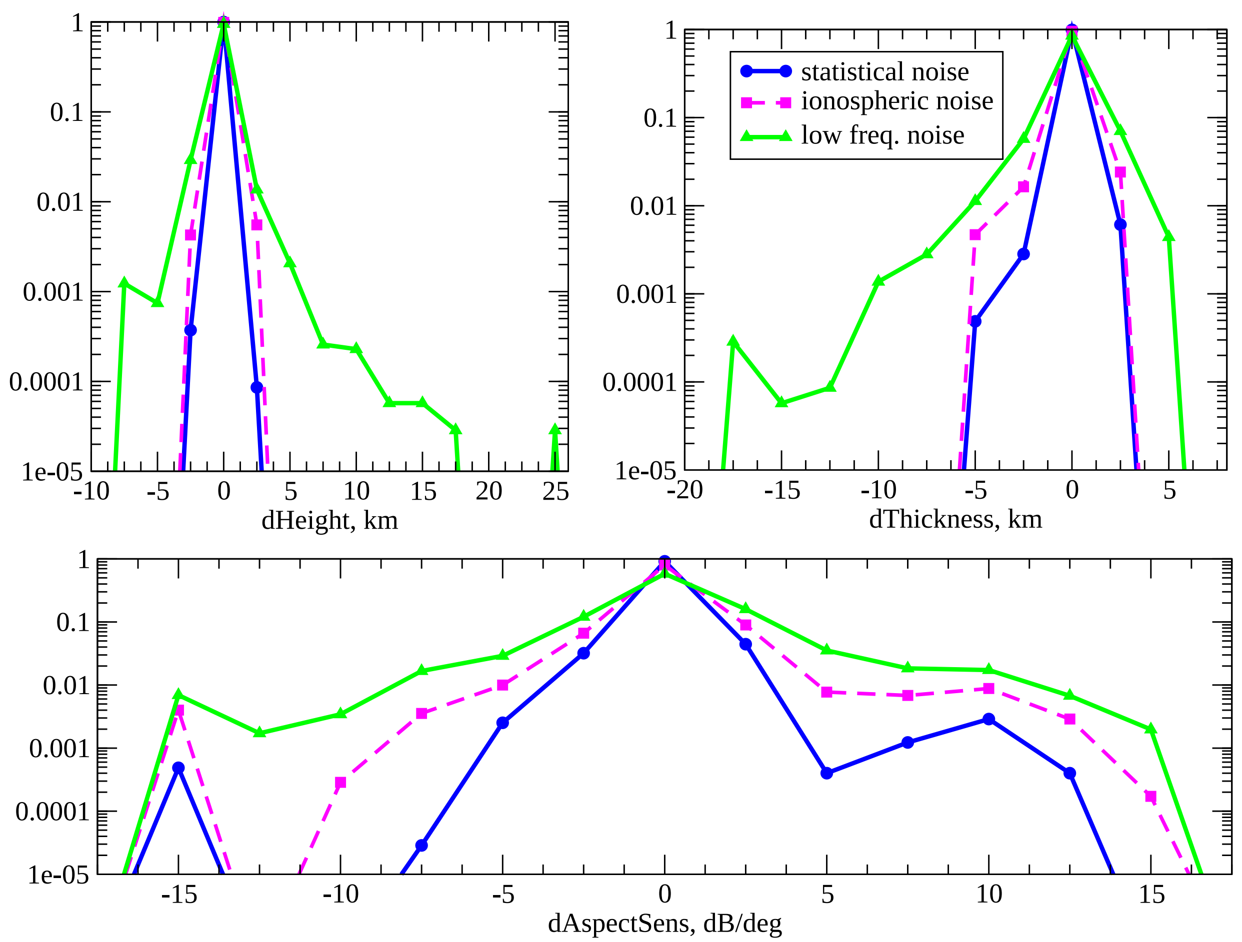

Fig 4b. Errors distribution of inverting noised experimental data (16.07.2000 experiment)

During the work the data obtained at Irkutsk IS radar was processed for strong geomagnetic storms on 25-26.09.1998 and 15-16.07.2000. The data processing has shown a successful agreement between the model and the experimental data (more than a half of the experimental profiles agrees with the experimental data, with the correlation coefficient 0.98, and in 90% of coherent echo observation cases the correlation coefficient is no less than 0.94). At fig.5a-b the dependence of the parameters (inverted with the described technique) on time is shown. From the fig.5a-b one can see that time dependence of irregularities layer parameters (especially its height and thickness) usually has smooth time variations. So we can explain power profile time dependence by variations of these parameters. This allows us to suppose the correctness of the model for description of the experimental data.

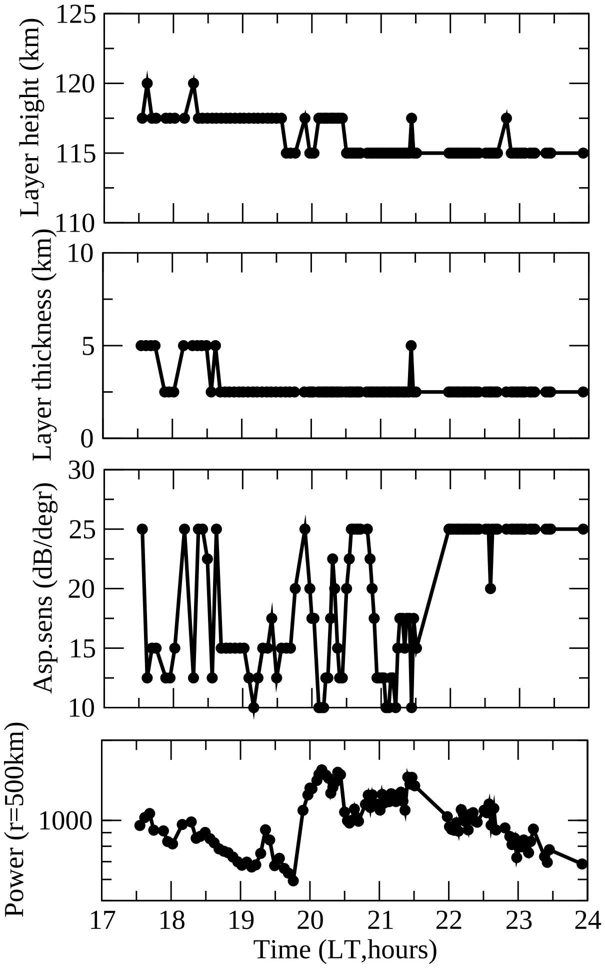

Fig 5a Experimental data processing results for 25-26.09.1998 experiment.

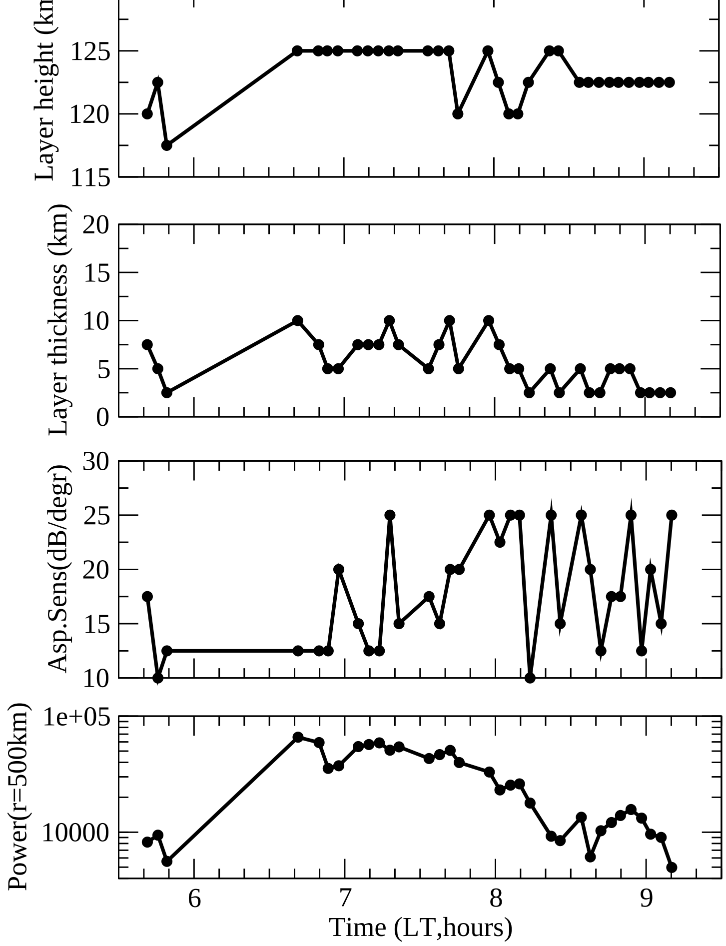

Fig 5b Experimental data processing results for 15-16.07.2000 experiment.

The fast variations observed especially in aspect sensitivity time variations could be caused by the following:

1. Non-optimal time resolution of the experimental data (for now ~ 4 minutes)

2. Latitudinal changes of the model parameters, not included into consideration. It is the electron-ion drift velocity, that could cause the most signifficant changes of any parameter.

3. Errors in the Irkutsk IS radar antenna pattern model (current model has not been calibrated at lower sidelobes, affecting to the power profile shape)

4. Not including into consideration an azimuthal aspect sensitivity of the irregularities (the model of scattered signal is isotropic in the plane perpendicular to the magnetic field, due to the fact that we do not know electric field direction exactly).

4 Conclusion

In the paper we have presented a technique of determining the scattering irregularities (that cause coherent echo) layer parameters using the Irkutsk IS radar data. It is shown that our technique has necessary accuracy (for height and thickness - about 2.5 km, for aspect sensitivity - 5dB/degree). Processing of the experiments 25-26.12.1998 and 15-16.07.2000 has shown a good agreement of data calculated with the data obtained by other investigators: an average layer height is 110-120km, average layer thickness 5km, average aspect sensitivity - 15dB/degree [Foster et al., 1992].

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